TERAHERTZ HETERODYNE RECEIVER WITH A HOT-ELECTRON BOLOMETER MIXER

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INTRODUCTION

During the past decade major advances have been made regarding low noise mixers for terahertz (THz) heterodyne receivers. State of the art hot-electron-bolometer (HEB) mixers have noise temperatures close to the quantum limit and require less than a µW power from the local oscillator (LO). The technology is now at a point where the performance of a practical receiver employing such mixer, rather than the figures of merit of the mixer itself, are of major concern. We have incorporated a phonon-cooled NbN HEB mixer in a 2.5 THz heterodyne receiver and investigated the performance of the receiver. This yields important information for the development of heterodyne receivers such as GREAT (German receiver for astronomy at THz frequencies aboard SOFIA) [1] and TELIS (Terahertz limb sounder), a balloon borne heterodyne receiver for atmospheric research [2]. Both are currently under development at DLR.

MIXER DESIGN

The HEB mixer was manufactured from a superconducting NbN film with a nominal thickness of 3.5 nm. The film was deposited by dc reactive magnetron sputtering on a 350 µm thick high resistivity (>10 kΩ cm) Si substrate [3]. The bolometer is located in the center of a planar antenna. Two types of antennas have been used: a logarithmic-spiral antenna and a double-slot antenna. The logarithmic-spiral antenna was designed to cover the frequency range from about 0.5 THz to 6 THz, while the double-slot antenna was optimized for 1.8 THz. In both designs the superconducting bridge has a width of 1.5 µm and a length of 0.2 µm. Due to processing its transition temperature of 9 K is slightly lower than the transition temperature of the film (10 K). The transition width and the square resistance increased slightly after processing (≈ 0.5 K and ≈ 660 Ω at 20 K). The substrate with the HEB was glued onto the flat side of an extended hemispherical 12 mm diameter silicon lens with a Parylene antireflection coating optimized for 2.5 THz [4]. The lens with the HEB was mounted on a copper holder, which in turn was directly screwed to the 4.2 K cold plate of liquid Helium cryostat with a wedged TPX pressure window and a cold (77 K) quartz filter. The intermediate frequency (IF) signal was guided out of the mixer via the arms of the antenna and 50 Ω coplanar line. A circulator was used to feed the bias to the mixer and to transmit the IF signal to a 4 K low noise HEMT amplifier. The output signal was filtered at 1.5 GHz with a bandwidth of 75 MHz, further amplified and rectified with a crystal detector.

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MIXER PERFORMANCE

Noise temperature and IF bandwidth

The measurements were performed using an optically pumped FIR ring laser [5] as LO. A rotating wire grid served for attenuation of the LO power. The signal radiation and the LO radiation were superimposed by a 6 µm thick Mylar beam splitter. The LO power transmitted by the beamsplitter was monitored with a Golay detector. The double sideband (DSB) noise temperature of the receiver was measured by the Y-factor method. Hot and cold loads (Eccosorb at 293 K and 77 K) alternatively covered the antenna beam of the mixer. The hot and cold signals were detected with a crystal detector and continuously readout by a computer, which performed statistical analysis of the signal and computed the noise temperature from the measured Y-factor. Fig. 1 shows the current-voltage (IV) curve of a typical mixer recorded at different LO power. Minimal noise temperature is achieved in the vicinity of the operation point A. Applying an isothermal technique we estimated 100 nW power absorbed by the HEB at the operation point corresponding to the minimum noise temperature. The best DSB noise temperature was 2200 K. We found that this figure does not noticeably decrease in the IF frequency range up to 2 GHz. This finding correlates with the expected noise temperature roll-off frequency of 6 GHz for this mixer [6].

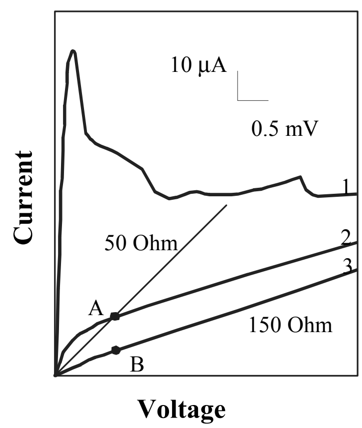

Figure 1: *IV-curve of the mixer (1: unpumped, 2: pumped by optimal LO power, 3 driven in normal state) The lowest noise temperature is achieved in point A.).*

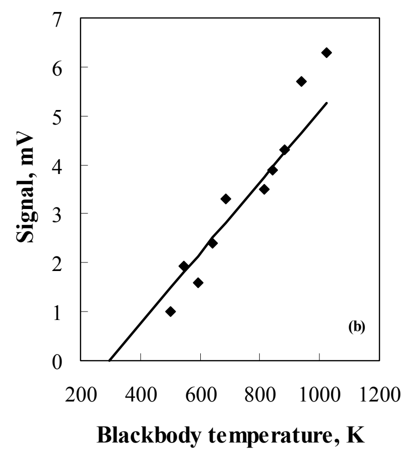

Figure 2*:Heterodyne signal as a function of the black body temperature.*

Dynamic range and conversion loss

In order to evaluate the dynamic range of the mixer we measured the heterodyne response at 2.5 THz to black body radiation while varying the black body temperature and keeping the aperture fixed. The result (Fig. 2) demonstrates the linearity of the response up to a temperature of 1050 K. The beam filling factor of the black body with respect to the antenna pattern of the mixer is 10% [7]. This results in a maximum non-saturating load temperature of ≈ 400 K at the mixer input. Since the signal shows no signs of saturation even at the largest black body temperature, we expect the 3 dB compression for our mixer at a load temperature significantly larger than 400 K. The slope of the line in Fig. 2 corresponds to a conversion efficiency of –17 ± 1 dB. This figure includes optical coupling losses, conversion efficiency of the mixer, and losses in the IF chain from the mixer output to the input of the cold amplifier. The optical losses at 2.5 THz are 4±0.5 dB [3]. The IF losses can be estimated by comparing the noise signals originating from a 50 Ω resistor and the mixer driven into the normal state (point B in Fig. 1). This yields 4±0.5 dB IF losses (for details see [7]). The remaining 9±1 dB loss are due to the conversion efficiency of the mixer. This is in agreement with the conversion efficiency calculated in the frame of the uniform large signal model [7].

Beam pattern

The beam patterns of hybrid antennas with a double-slot and a logarithmic-spiral feed antenna are shown in Fig. 3 (lens diameter is 12 mm in both cases). Both patterns were measured at a LO frequency of 1.6 THz by moving a hot source in the far field of the mixer. The output signal of the mixer was registered as a function of the position of the hot source. The solid line is fit of a Gaussian profile to the main lobe. It yields a 3 dB width of 1.1 and 1.3° for the double-slot and logarithmic-spiral feed antenna respectively. The sidelobes are at –10 dB or below and at –6 dB, indicating that at this frequency the double-slot feed antenna is the better choice. However, this may change at higher frequencies where the dimensions of the double-slot antenna become comparable to the size of the HEB and the IF circuitry.

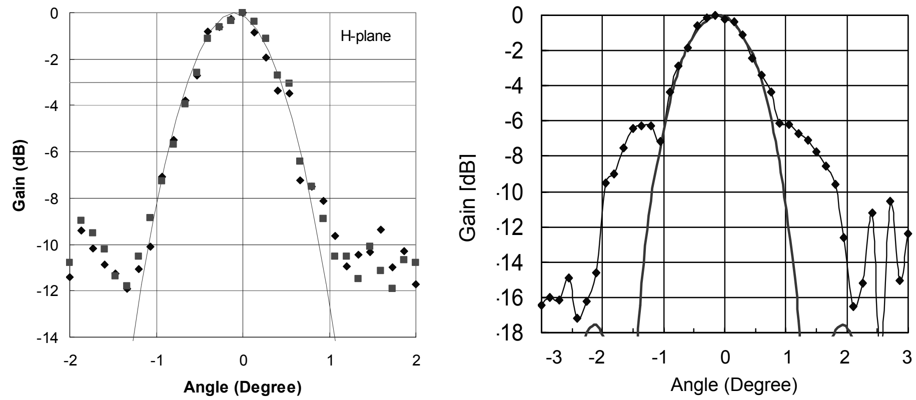

Figure 3: *Antenna pattern of hybrid antennas with double-slot (left) and logarithmic-spiral feed antenna(right) and 12 mm lens. The heterodyne signal at the LO frequency of 1.6 THz is plotted*

Noise stability

The noise temperature of a mixer is an important figure of merit. If the noise in the receiver is completely uncorrelated (i.e. white) the radiometer equation states that the noise integrates down with the square root of the integration time. However, in practice the total noise of a receiver is a combination of white noise, 1/f noise and low frequency drift noise. For an analysis of the noise stability of a receiver it is useful to consider the "Allan" variance, σ_A, given by $\sigma^2_A(t)=1/2\sigma^2(t)$, where σ is the standard deviation of the signal [8]. For a noise spectrum that contains white noise, 1/f and drift noise the "Allan" variance takes the form $\sigma^2_A(t)=at^\beta+b/t+c$, where a, b, c and β are constants which depend on the specific situation. Therefore an optimum integration time ("Allan" stability time, t_A) exists, which is the crossover from white noise to 1/f or drift noise. Fig. 4 displays the mean square output signal ("Allan" variance) as a function of integration time for two different bias points. For an operation point in the linear part of the IV-curve (A) the "Allan" time is 5 s and the DSB noise temperature is 5500 K while it is only 0.1 s for an operation point in the nonlinear part (B) although the DSB noise temperature is much better (1500 K).

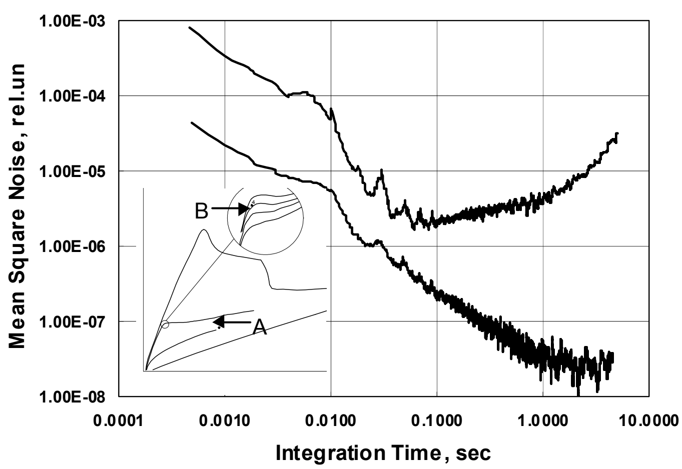

***Figure 4:*.** *"Allan" variance as a function of time for two different operation points (see inset).*

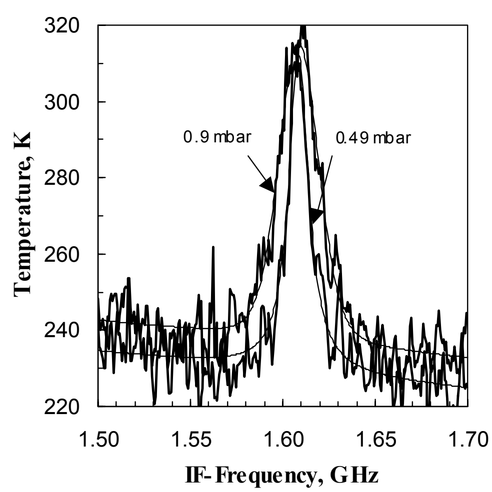

Figure 5: *Methanol emission lines measured at 0.49 mbar and 0.90 mbar (LO frequency: 2.52278 THz).*

SPECTROSCOPY

As a final test we recorded an emission line from methanol in a gas cell with 50 cm absorption length. The line is located in the upper sideband 1.61 GHz separated from the 2.52278 THz methanol laser line. An acousto-optical spectrometer was used as the backend spectrometer. The gas was kept at ambient temperature. Behind the cell a 77 K blackbody was placed. Signal radiation and the LO radiation were superimposed by a 6 µm thick Mylar beamsplitter. Fig. 5 shows spectra measured at pressures of 0.49 mbar and 0.9 mbar. The temperature scale shows single sideband values. The line was opaque in the center. Thus the signal should not be larger than 296 K. The increase may be due to the sideband ratio deviating from one or due to alignment errors. The smooth line is a Voigt profile with a linear background which was fitted to the measured profiles. The full width half at maximum (FWHM) of the lines is 13 MHz (0.49 mbar) and 26 MHz (0.90mbar). This corresponds well with the expected linewidth deduced from pressure broadening measurements at millimeter wavelengths (13 MHz and 24 MHz).

CONCLUSION

We have demonstrated the practical usability of the NbN HEB mixer for heterodyne detection at THz frequencies. Noise temperature and noise stability are strongly dependent of the operating point of the mixer. The results demonstrate that the noise temperature as determined by the Y-factor method is not sufficient as a figure of merit. A statistical analysis of the noise stability of the receiver is required. The dynamic range of the HEB mixer is sufficient for applications in astronomy and atmospheric research. This is confirmed by spectroscopy of a methanol emission line with a HEB mixer. The line shape corresponds to the theoretical expectations.

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